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A PHASED ARRAY MAINTENANCE MONITORING SYSTEM. PART II.(U)
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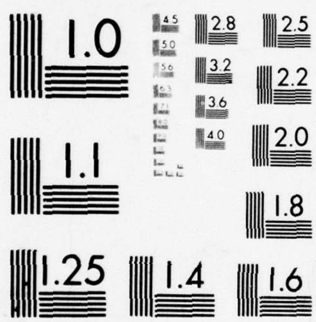
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NRL Memorandum Report 3737

A Phased Array Maintenance Monitoring System
Part II

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J. K. Hsiao and J. P. Shelton

Target Characteristics Branch
Radar Division

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20. Abstract (Continued)

they are adequate to detect and locate failure in both the network and the phase shifters in a COMPACT phased array.

CONTENTS

A PHASED ARRAY MAINTENANCE MONITORING SYSTEM

PART II

INTRODUCTION

In Part I of this two-part series of reports [1], an integrated maintenance monitoring system for detecting and locating failures in a conventional phased array has been described. Two systems were proposed to perform such a task, and the performance of the systems was simulated. Results of these simulations indicated that the monitoring systems could locate failures in a satisfactory manner. In this report, a maintenance monitoring system used in a COMPACT phased array system is described.* COMPACT, originally proposed by Hazeltine, utilizes an auxiliary feed network to achieve a desired limited-coverage array element pattern. If this element pattern is properly shaped, the number of phase shifters in the array can be reduced without the appearance of high grating lobes when the array scans only a limited range. This may reduce the cost of an array system. Currently studies of the application of COMPACT in the Microwave Landing System are underway. Maintenance monitoring of such array systems is part of this study. In this report, results of studies of this problem undertaken at the Naval Research Laboratory (NRL) are presented.

Two maintenance monitoring systems for a COMPACT array will be described in this report. One of them is the Fourier transform method which has been discussed in Part I. The second one is referred to as a one-bit-transformation (or Hadamard transformation) method. This method transforms the input manifold signal for failure detection by simple addition and subtraction. It thus avoids the use of complex multiplication required in the Fourier transform method. Performance of these two systems has been simulated and results are presented.

FAILURE MODES OF A COMPACT ARRAY

The auxiliary feed network of a COMPACT array is shown in Figure 1. Operational principles and concepts of a COMPACT array are described in

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* COMPACT is an essentially meaningless acronym for "cost minimized phased array circuit technique." It is actually a network which produces sector element patterns from a linear array while reducing the number of element ports by a factor of two.

Note: Manuscript submitted February 28, 1978.

detail in Appendix A. Referring to Figure 1, the power fed from each phase shifter is actually distributed to every radiating element in the array through a coupling network. The network contains two independent, transverse, directionally coupled transmission lines. One line feeds the radiating elements to the left side of the phase shifter and the other feeds the right-side elements. Three failure modes are postulated for the COMPACT network. The first mode is a failure at the power divider from the phase shifter to the COMPACT network. The second mode is a failure which may occur between the COMPACT network and the radiating elements. The third mode is a failure located in the transverse transmission line within the COMPACT network. These failure modes are marked on Figure 1. For simplification, in the following simulation it is assumed that these failures are open-circuit type. Since the two transverse transmission lines are symmetric, failures in only one of the transmission lines are simulated. Besides these three failure modes, the phase shifter may also have a stuck-to-one or a stuck-to-zero error, as discussed in Part I.

Two failure detection algorithms were simulated. One is the Fourier transform method and the other is the one-bit-transform (or Hadamard transform) method. The algorithms and results of the simulations are presented in the following two sections.

FOURIER TRANSFORM METHOD

The Fourier transform method used here is similar to that described in Park I. In this algorithm, each phase shifter of the array is cycled through all possible states in a progressive sequence. Outputs from the manifold are coherently detected and digitized, and a Fourier transform is performed. Outputs from this transform are then used for detection of failures as illustrated in Figure 2. This process is identical to that of the maintenance system of a conventional array. For details of such a system readers are referred to Part I of this report. However, there are differences for present applications. In a COMPACT array, power from each phase shifter is actually fed through the coupling network to every radiating element in the array. Therefore, the effect of this coupling network must be taken into account. This coupling network as shown in Figure 1 is actually formed by 3-dB directional couplers.* These couplers are connected in series to split the power fed from the phase shifter to the radiating element directly above it and to successive elements at the right side or the left side of this phase shifter. Attenuation is inserted in the transverse transmission line between successive radiating elements to achieve additional control over the element pattern. Each of the 3-dB couplers is subject to both phase and amplitude errors. Since the sources contributing to these errors are independent and numerous, it

*The coupling coefficient of the directional couplers is a selectable design parameter. The preferred value is about 3 dB.

is assumed that these errors have a Gaussian distribution, by invoking the central limit theorem. As mentioned earlier, three modes of failures are assumed. However, in the following simulation, it is assumed that only one failure occurs at a time.

From Figure 1, one may see that failures occurring in the COMPACT network have equal effect on all states of a given phase shifter. Therefore, this kind of failure cannot be detected by observing the higher harmonics obtained from the Fourier transform operation. On the other hand, network failure might be detected by measurement of the amplitude of the output from the monitoring manifold. For better likelihood of failure detection, one may sum the amplitudes of the output from the manifold for all phase shifter states. These outputs can be represented

$$f_k = ae^{j\phi} + A_k e^{j(k\ 2\pi/N + \xi_k)};\ k = 1, --- N \tag{1}$$

where N is the total number of phase shifter states. Ignoring the residual signal term, $ae^{j\phi}$ one finds the sum of the magnitudes of manifold outputs is approximately

$$S \approx \sum_k A_k \tag{2}$$

$$= NA,$$

where $A = \Sigma A_k/N$.

The fundamental frequency component of the Fourier transform of the manifold outputs is

$$F = \sum_k f_k\ e^{-j(k2\pi/N)}$$

$$= \sum_k A_k\ e^{j\xi_k} \tag{3}$$

The absolute value of F is approximately, for ξ_k small,

$$|F| \approx NA \tag{4}$$

Therefore, observing the level of the output at the fundamental frequency component is a possible method of detecting failures in the COMPACT network.

To investigate the feasibility of such a monitoring system, a computer simulation was conducted. In this simulation program, it is assumed that the array has 116 radiating elements. Elements are

connected in pairs through the power dividers, then to the COMPACT network. Thus, there are 29 phase shifters. The attenuation value between successive couplers is set at 4.25 dB.

It is assumed that the phase and ampitude of both phase shifter states and network coupling coefficients are subject to random error. The distribution of this random error is Gaussian. The amplitude distribution has zero mean and a selectable standard deviation. The phase shift distribution has selectable mean and standard deviation. These random errors are generated in the computer and assigned to each phase shifter and coupling network at the beginning of each simulation cycle.

In the process of computing one simulation cycle, every phase shifter in the array is cycled through all possible states one at a time. The monitored outputs for a given phase shifter are stored, and a Fourier transform of these outputs is performed and stored. Outputs from the Fourier transform network are harmonically grouped for detection of various bit failures as shown in Figure 2. The maximum output of each harmonic group is selected and stored. For each shifter, the no-failure case is first computed. Then the various failure modes are selected, and the outputs are computed and stored. This procedure is performed on each phase shifter in the array to complete one simulation cycle. After the simulation cycle is completed for the entire array, a different set of phase and amplitude errors are assigned to all phase shifters and coupler networks, and the process is repeated.

A stochastic random noise is also assumed during the simulation. This noise may be due to either thermal noise in the system or measurement errors. This noise is specified in terms of a signal to noise ratio and is assumed to have a Rayleigh distribution. It is also assumed that these noise components vary with each measurement.

A large number (about 1000) of simulation cycles were computed. The cumulative probability distributions of the monitor system output levels were then computed and normalized with respect to the maximum output level.

Figure 3a shows the cumulative probability distribution of the output level for each bit failure detector. For each bit there are two curves. The left-hand curve represents the case of no failure or failure on another bit. In this plot the phase shifter amplitude error has a standard deviation of .1 of its normal amplitude while the standard deviation of phase error is 4 degrees. For the coupling network, the amplitude error has a standard deviation of .05 and the phase error has a standard deviation of 5 degrees. A 20 dB signal-to-noise ratio is assumed in this simulation. For these curves, it is seen that one can easily choose a threshold level such that any bit failure can be detected with a probability of almost 100 percent with a negligible probability of false alarm. Figure 3b shows the cumulative probability distribution of output level at the failure detector

for the COMPACT network. It shows that it is possible to detect network failures of the first and second types. However, there is a small probability that a failure of the third type cannot be detected. This is because failures occurring at the end of the coupling network have very little effect on the manifold output. Such failures have a correspondingly small effect on the performance of the system, so the inability to detect them is of minor importance. Figures 4a and 4b show the same probability distributions when the errors in the coupling network have an amplitude standard deviation of .1 and a phase standard deviation of 10 degrees. Comparing these plots with those of Figures 3a and 3b, one sees that an increase in the errors in the coupling network has very little effect on the performance of the monitor system. Figures 5a and 5b show the case of a signal-to-noise ratio of 10 dB and with the same amplitude and phase errors as for the case of Figures 4a and 4b. These figures indicate that it is very difficult to choose a threshold level which will give a reasonably good detection probability together with low probability of false alarm. It is concluded that, in order to successfully implement this monitoring system, a signal-to-noise ratio of about 20 dB is required.

The effect of variation of the level of random errors in the phase shifters was treated in Part I of this report. Since the effect is similar for a COMPACT array, no further study was conducted.

ONE-BIT TRANSFORM METHOD

In the Fourier transform method, input signals have to be phase shifted in order to find the frequency component. This phase shifting usually involves a complex multiplication in the processor. However, this complex multiplication can be avoided if a one-bit transformation is used. The algorithm of such a process is presented as follows:

The output reference from the manifold at each phase state is represented as

$$f_k = A\, e^{j\phi} + A_k\, e^{i(k\, 2\pi/N + \xi_k)} \quad k = 0, \text{---}\ N-1$$

where N is the total number of phase states and ξ_k is the phase error in each state while $A\, e^{j\phi}$ is the residual signal in the system. The following set of signals from these inputs (for a 4 bit phase shifter) is formed:

$$F(1) = |f_o - f_1| + |f_2 - f_3| + \text{- - -}\ |f_{N-2} - f_{N-1}| \tag{5a}$$

$$F(2) = |f_o - f_2| + |f_1 - f_3| + \text{- - -}\ |f_{N-3} - f_{N-1}| \tag{5b}$$

$$F(3) = |f_o - f_4| + |f_1 - f_o| + \text{- - -}\ |f_{N-5} - f_{N-1}| \tag{5c}$$

$$F(4) = |f_o - f_8| + |f_1 - f_9| + \text{- - -}\ |f_{N-9} - f_{N-1}| \tag{5d}$$

The F(1) function is used to detect failures in the first bit. In case of failure in the first bit, the f_o is identifical to f_1 and f_2 is identical to f_3, etc. Hence, in this case, F(1) would have a zero output. On the other hand, if the first bit has no error, then F(1) will have a finite value. Similarly, one can use F(2) to detect failures in the second bit, F(3) for the third bit and F(4) for the fourth bit.

Results of a computer simulation of such a system are shown in Figures 6, 7 and 8. The conditions for the plot of Figure 7 are identical with those of Figure 3. It is assumed that the phase shifter has an amplitude error of .1 and phase error of 4 degrees while in the coupling network they are respectively .05 and 5 degrees. Signal to noise ratio is assumed to be 20 dB. For each bit, there are two curves. The right-hand curve represents the case of no failure, while the left-hand curve represents failure in one of the bits. Thus, the one-bit transform method is different from the Fourier transform method. When the signal is above a threshold, it represents a normal or no failure situation, while a signal below the threshold represents the failure case. As an example, if one sets a threshold level of .13 at the first bit detector, one sees there is almost zero probability that the output will be greater than this threshold when a failure occurs. This may be interpreted as an almost 100 percent failure detection probability. On the other hand, only 97 percent of the samples have an output level greater than this threshold when no failure occurs; therefore, a false alarm of 3 percent can be expected. For other bits, it is evident that failure detection can be easily achieved.

Figure 7 shows for the case of a phase error of 10 degrees and amplitude of .1 in the coupler, while Fgiure 8 shows a case of a signal to noise ratio of 10 dB.

From these figures one may draw a similar conclusion that a signal to noise ratio of about 20 dB is required for an effective failure detection. Required component tolerance seems to be within a reasonable range as in the case of the Fourier transform method.

To detect a failure in the coupling network, one may use the same approach as in the Fourier transform method, in which the amplitudes of the manifold outputs are summed as the phase shifter is cycled through its states.

In the above approach, the detection signal is formulated by summing the difference of pairs of input signal of the corresponding phase shifter bit. Thus, if that phase bit failed to switch consistently in a complete phase-state cycle, a minimum output from that bit detector line will be observed. However, there are cases for which the phase shifter may fail to switch part of the time during a complete phase-state cycle. To monitor such a failure mode, one may form the detection signals in a different way such that

$$F(1) = S \{|f_o - f_1|, |f_2 - f_3|, ---, |f_{N-2} - f_{N-1}|\} \quad (6a)$$

$$F(2) = S \{|f_o - f_2|, |f_1 - f_3|, ---, |f_{N-3} - f_{N-1}|\} \quad (6b)$$

$$F(3) = S \{|f_o - f_4|, |f_1 - f_5|, ---, |f_{N-5} - f_{N-1}|\} \quad (6c)$$

$$F(4) - S \{|f_o - f_8|, |f_1 - f_9|, ---, |f_{N-9} - f_{N-1}|\} \quad (6d)$$

where S means the smallest value of the members in the bracket.

Simulation results of such a detection algorithm are shown in Figure 9, and it is seen that an intermittent failure in the first bit would be very difficult to detect.

Figure 10 shows simulation results for the application of the one-bit transformation monitoring system to a conventional phased array. The phase shifter amplitude and phase errors are indicated in the figure. Comparison of Figure 10 with Figure 7 for the case of a COMPACT array indicates that their monitoring capability is essentially the same.

CONCLUSION

In this report, methods for monitoring both phase shifter and network failures in a COMPACT array are presented. A Fourier transform method, which was previously simulated for the case of a conventional array, (see Part I of this report) can be applied to the COMPACT array. A second method which uses a one-bit transform avoids the use of complex multiplication. Simulation of these two approaches indicate that they are adequate to detect and locate failures in a COMPACT phased array.

REFERENCE

[1] J. K. Hsiao and J. P. Shelton, "A Phased Array Maintenance Monitoring System, Part I," NRL Memorandum Report 3613, September 1977.

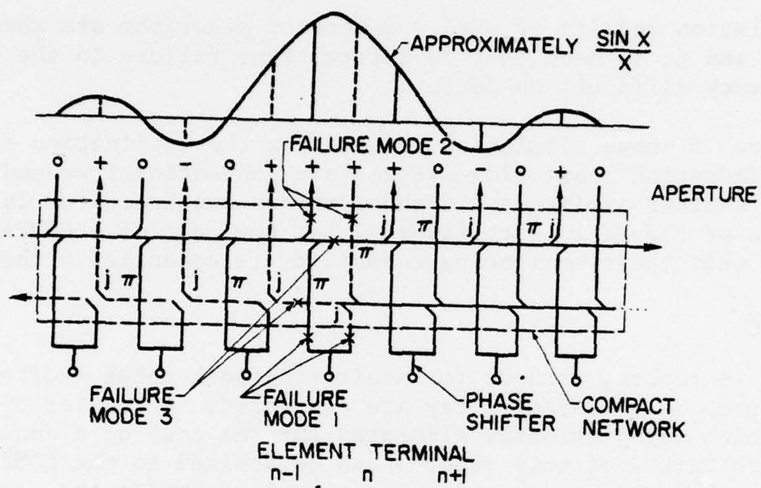

Fig. 1 — A COMPACT array feed network

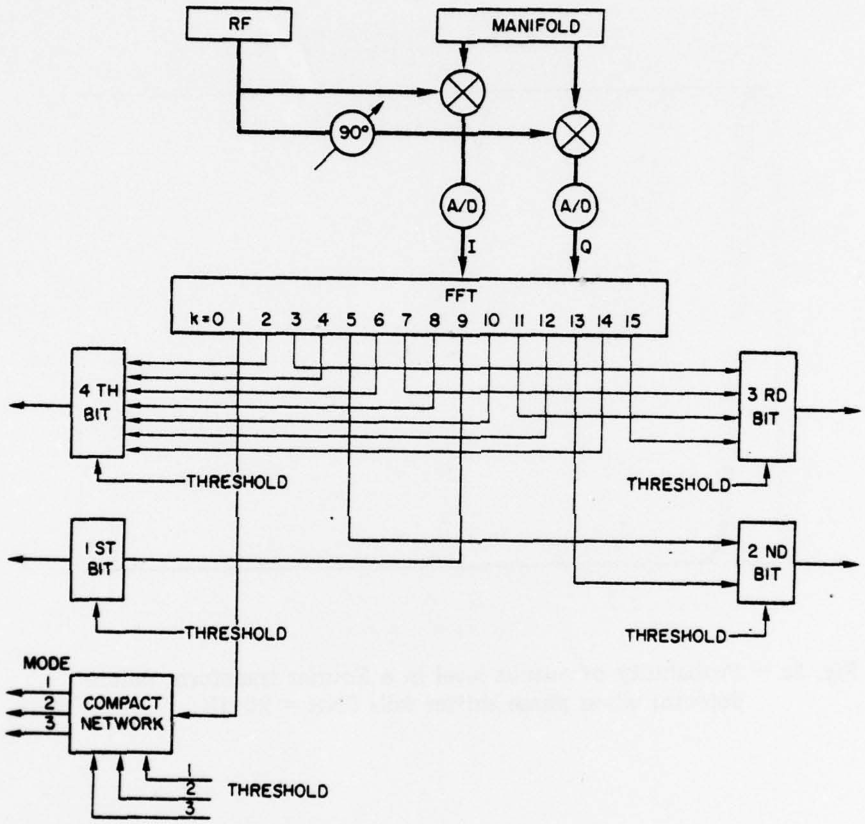

Fig. 2 — Fourier transform method for maintenance monitoring of a COMPACT array

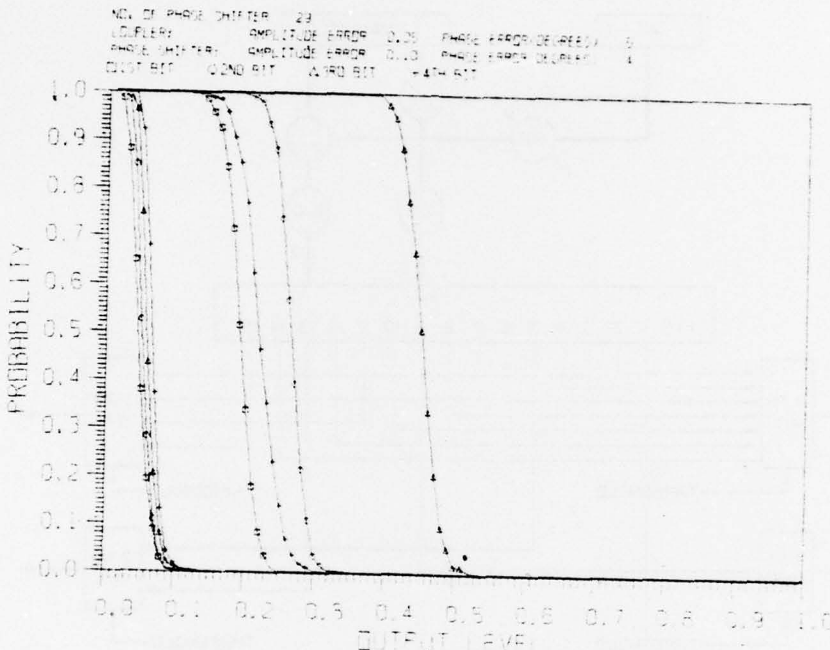

Fig. 3a — Probability of output level in a Fourier transform failure detector when phase shifter fails SNR = 20 dB

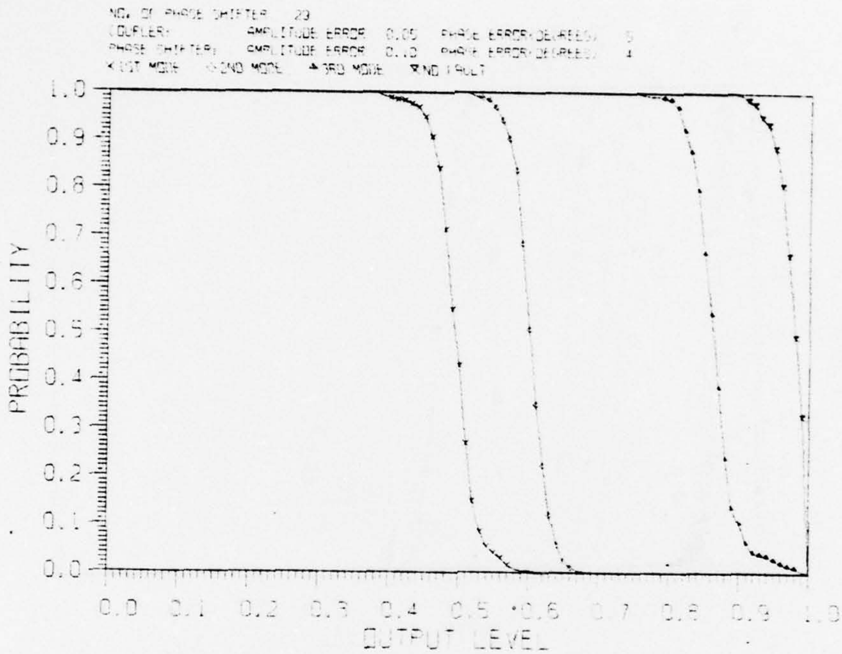

Fig. 3b — Probability of output level in a Fourier transform failure detector when coupling network fails SNR = 20 dB

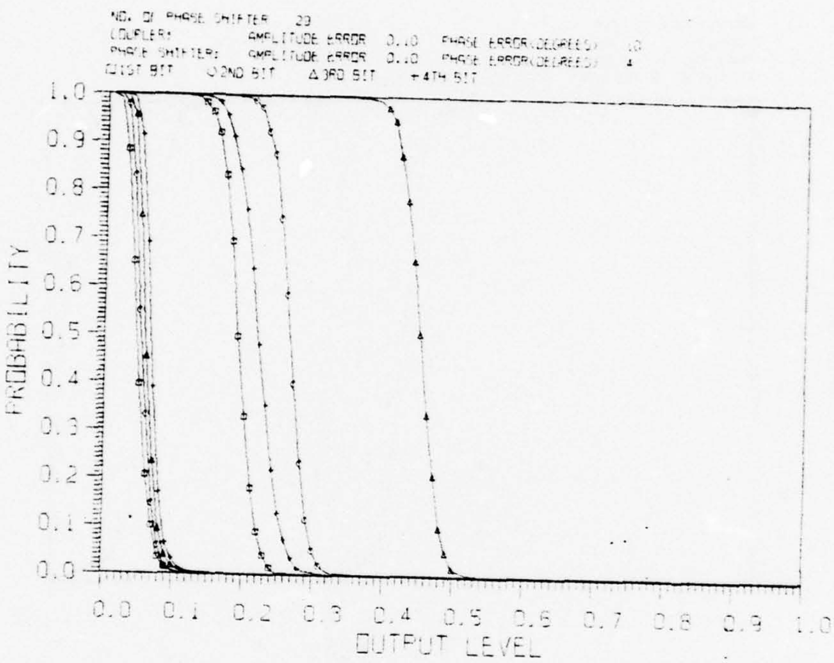

Fig. 4a — Probability of output level in a Fourier transform failure detector when phase shifter fails SNR = 20 dB

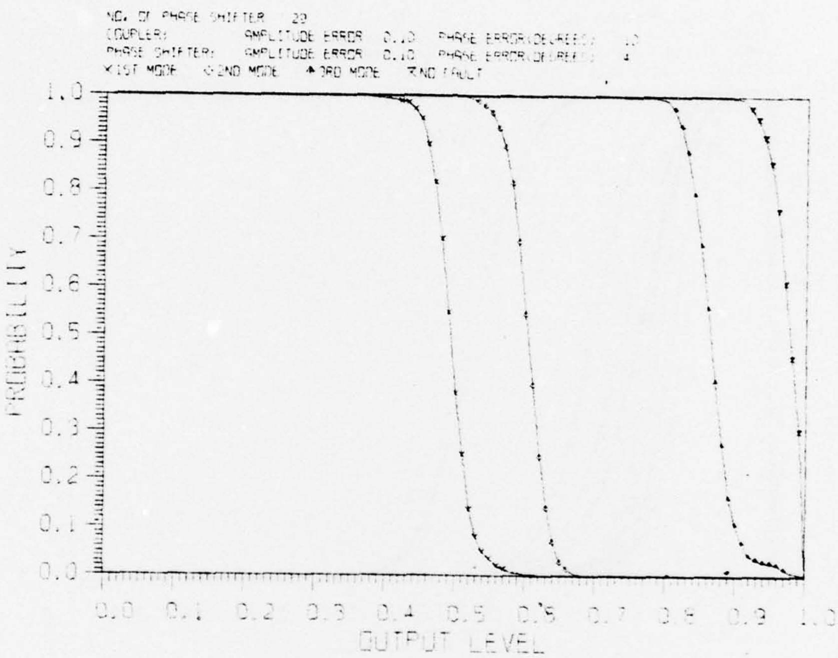

Fig. 4b — Probability of output level in a Fourier transform failure detector when coupling network fails SNR = 20 dB

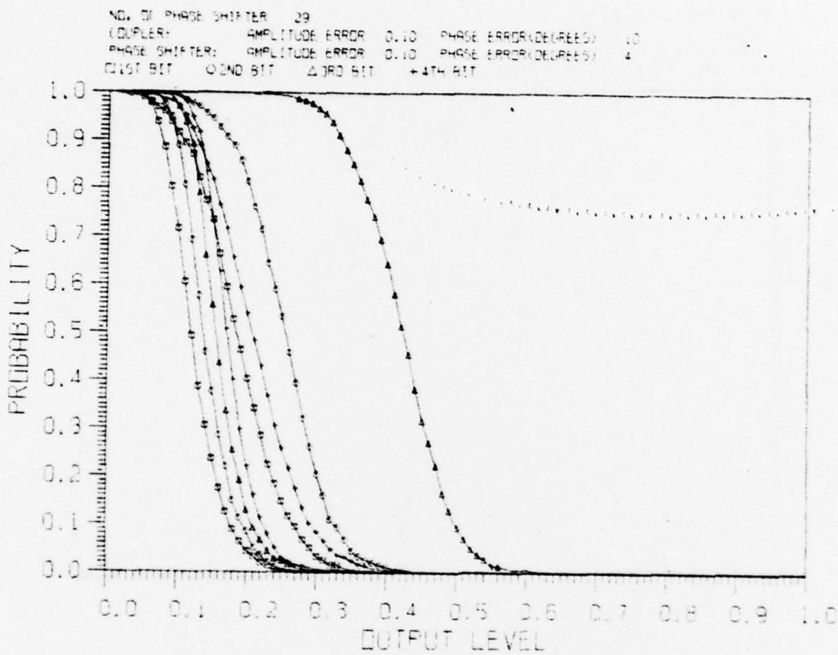

Fig. 5a — Probability of output level in a Fourier transform failure detector when phase shifter fails SNR = 10 dB

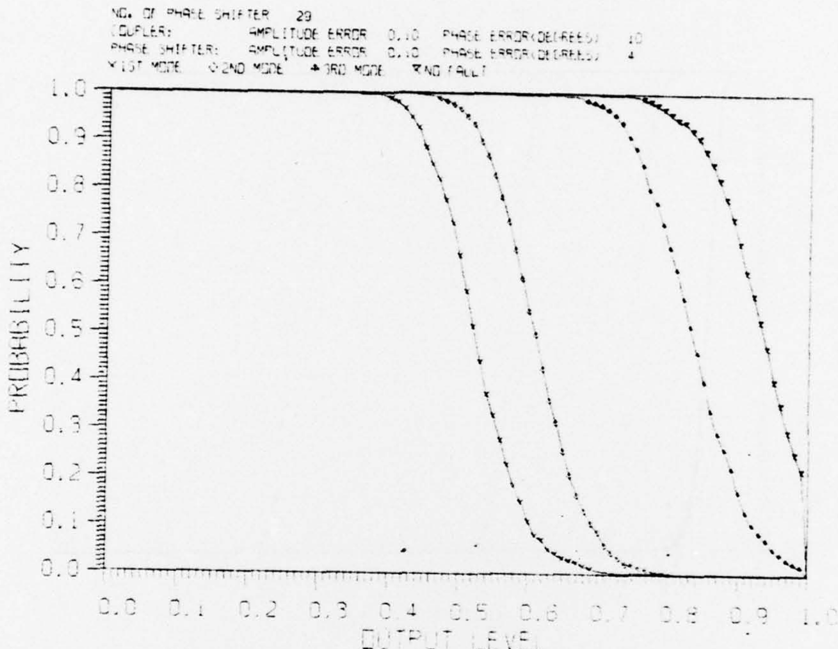

Fig. 5b — Probability of output level in a Fourier transform failure detector when coupling network fails SNR = 10 dB

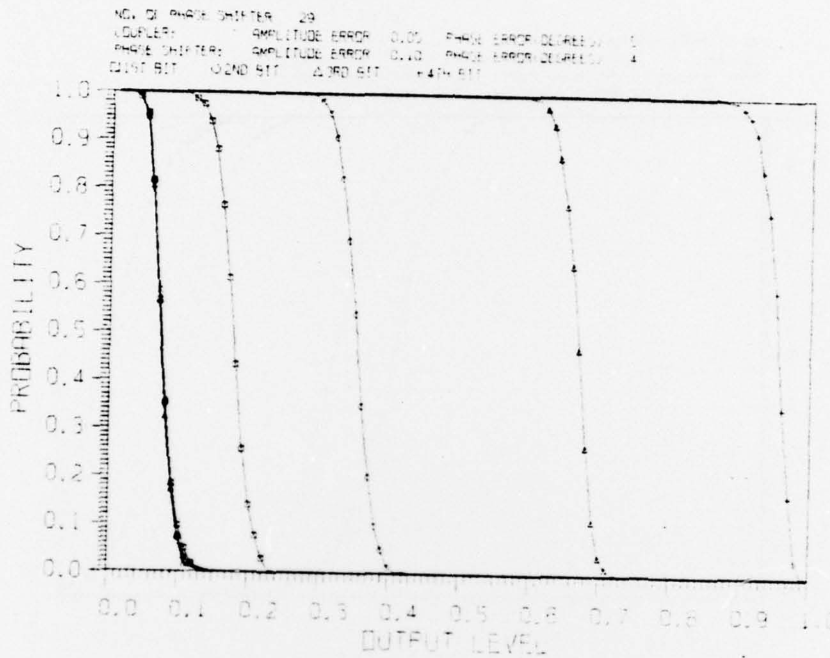

Fig. 6 — Probability of output level in a one-bit transform failure detector when phase shifter fails SNR = 20 dB

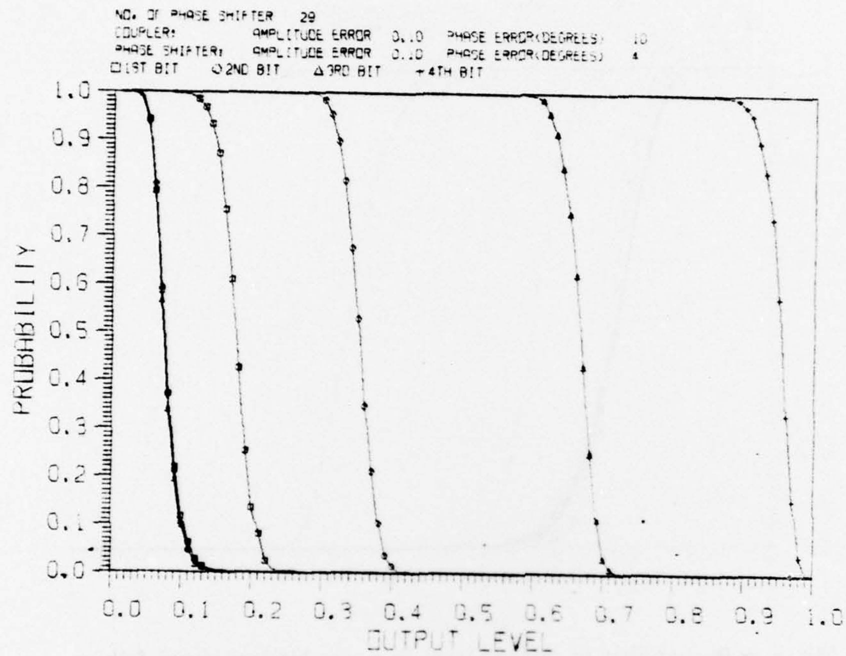

Fig. 7 — Probability of output level in a one-bit transform failure detector when phase shifter fails SNR = 20 dB

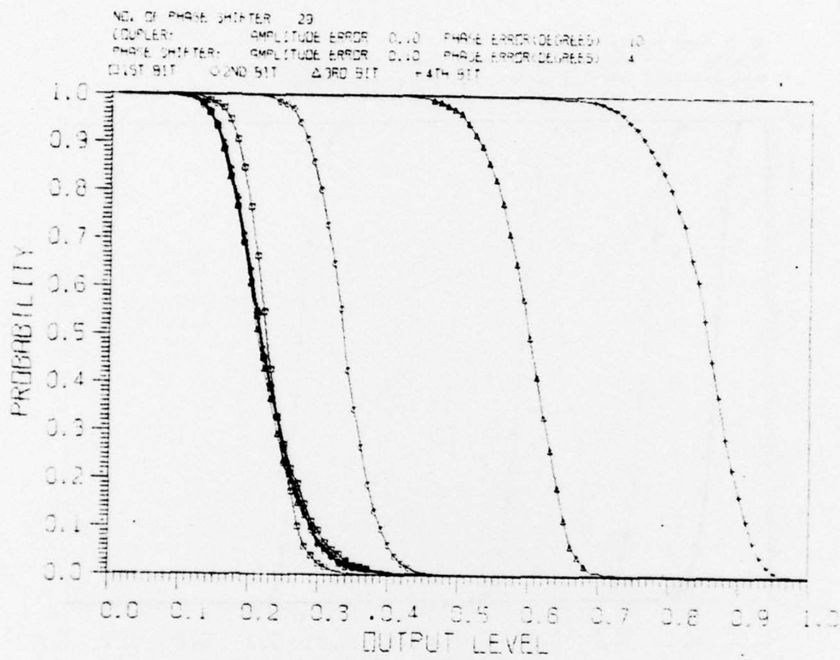

Fig. 8 — Probability of output level in a one-bit transform failure detector when phase shifter fails SNR = 10 dB

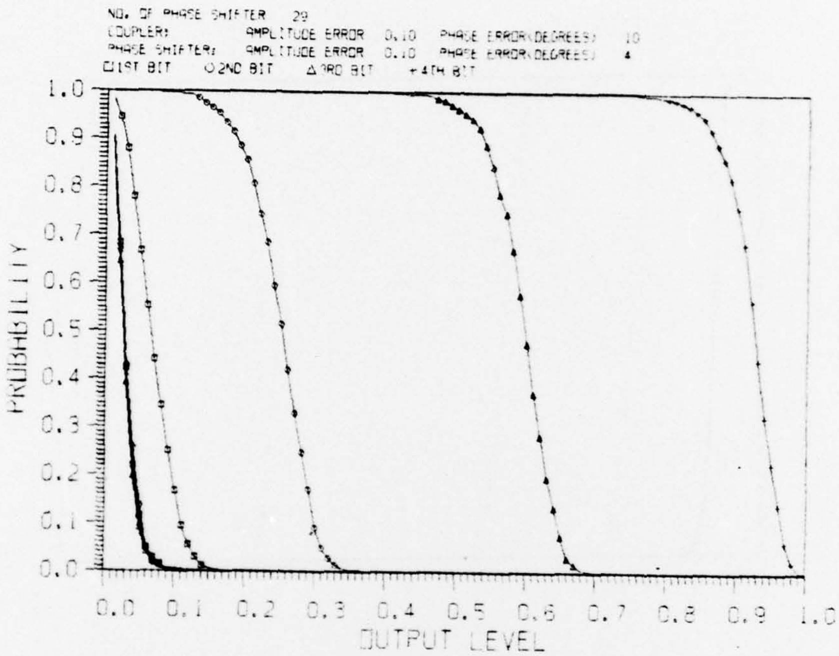

Fig. 9 — Probability of output level in a one-bit transform failure detector when phase shifter has intermittent failures, SNR = 20 dB

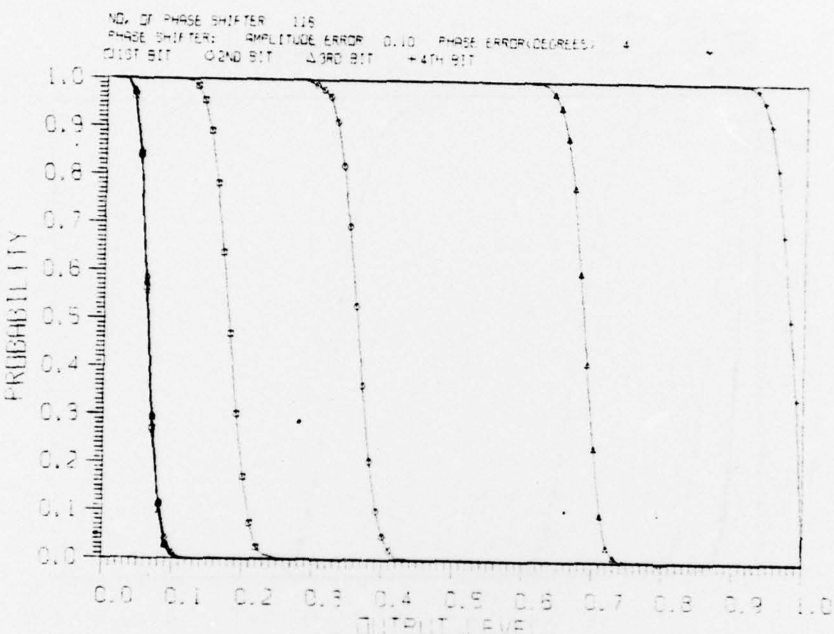

Fig. 10 — Probability of output level in a one-bit transform failure detector for a conventional array

APPENDIX A

Figure A-1 shows that the ideal COMPACT element pattern is obtained by an element that produces an aperture excitation that is in the form of sin x/x. The width of the "mainlobe" of the distribution in wavelengths and the sharpness of the pattern cutoff is proportional to the antenna aperture size, typically on the order of a few degrees wide.

Figure A-2 shows a block diagram of a typical COMPACT antenna. It consists of a power divider network, one phase shifter per effective element, a coupling network and individual radiators. The power divider network is used to excite the element terminals with a tapered distribution that yields an acceptable sidelobe level for the scanning beam pattern. The phase shifters shown at the element terminals are exercised to scan the narrow beam. Inserted between the element terminals and the radiators in the aperture is a coupling network. This network is a key component whose function is to provide the sin x/x element terminals. The network must provide translational symmetry; that is, each element terminal excites the same sin x/x distribution in the aperture only translated in the aperture by the separation of the element terminals.

Before describing the actual COMPACT coupling network, the basic method of generating sin x/x with translational symmetry is shown in Figure A-3. The network synthesis starts with a horizontal coupling line and vertical element lines connected to it by identical directional couplers. A portion of a signal input at one of the element lines is directly transmitted to the output of that element line and the remaining portion then excites all element lines to the right of the input by means of the directional couplers. This repeated coupling process results in an amplitude distribution which monotonically decreases to the right of the element terminal input. The phasing along the coupling line between directional couplers is π radians (180° of phase shift). This value of phase is chosen to produce the correct in-phase polarity of the output distribution mainlobe and the alternating-phase polarity of the sidelobes, as in the sin x/x function. As shown in the figure, the inherent property of a directional coupler is that the coupled output is in quadrature (j) (90° of phase shift) with the directly transmitted output. By tracing the signal input through this basic network, it can be seen that the proper polarity is achieved. This network, however, generates only one half of the desired aperture excitation, and the sampling points of sin x/x are rather widely spaced. To generate the complete sin x/x function and with more sample points, two identical coupling lines are interleaved and combined at the botton of the network to form the element terminal. The directional couplers in the top coupling line excite one side of the aperture. The directional

couplers in the bottom coupling line excite the opposite side of the aperture. The couplers are identical in both coupling lines only oriented in opposite directions. By tracing signals through this network, it can be seen that an element terminal excites a sin x/x type distribution in the aperture with four samples within the mainlobe, one sample at each of the zeros, and one sample at the peak of each sidelobe. This network is representative of the coupling network required in COMPACT.

The network of Figure A-1 has the required translational symmetry to form an array antenna. Each element terminal excites the same aperture distribution only displaced by the element spacing because the network is identical as seen from each element terminal.

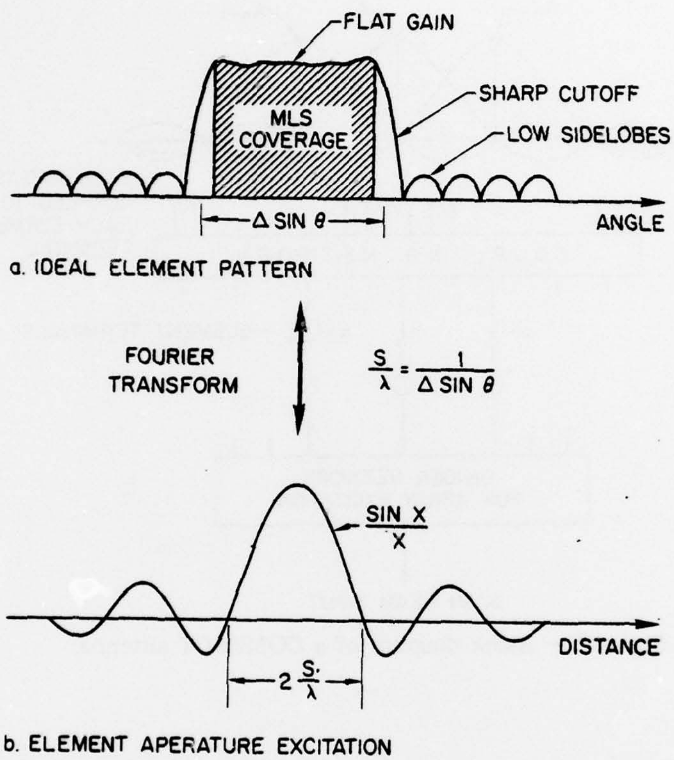

Fig. A-1 — Ideal COMPACT element pattern and aperture excitation

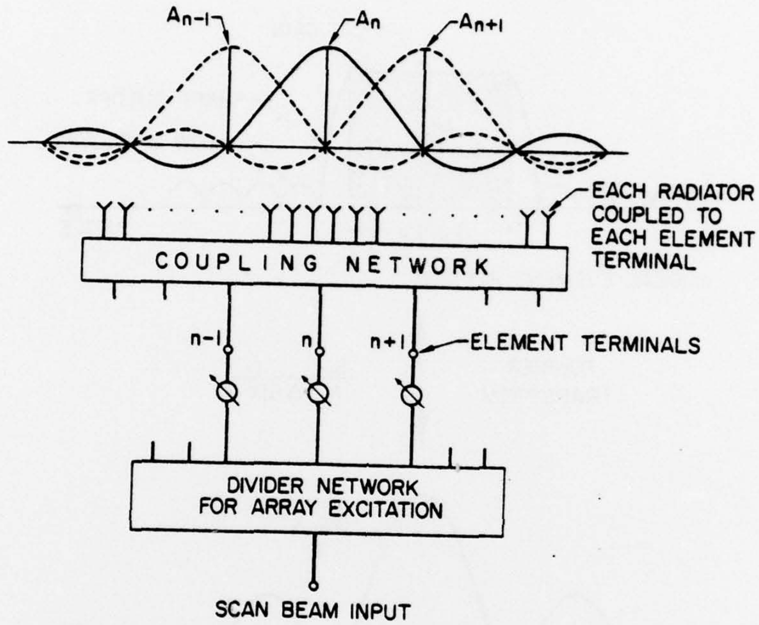

Fig. A-2 — Block diagram of a COMPACT antenna

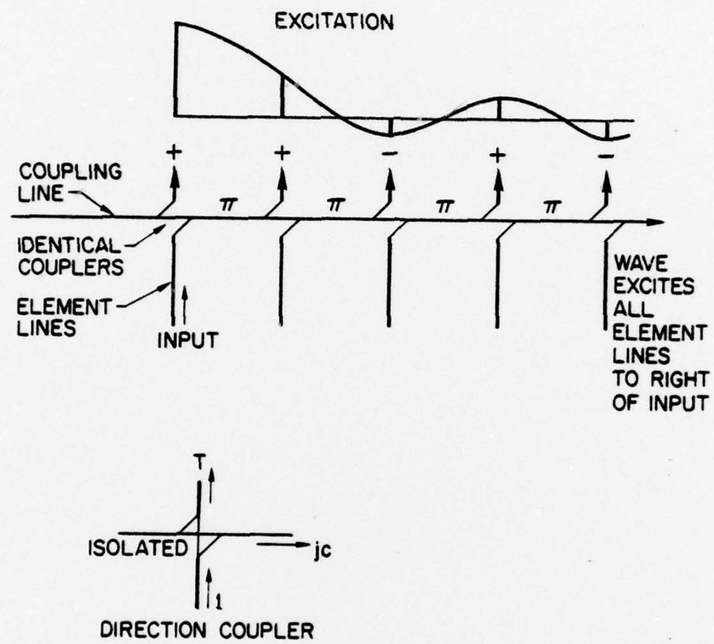

Fig. A-3 — Principle of COMPACT coupling network

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D ARRAY MAINTENANCE MONITORING SYSTEM, PART II.

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FOR MONITORING FAILURES IN A COMPACT ARRAY ARE PRESENTED. A FOURIER
RM METHOD CAN BE USED TO MONITOR A CONVENTIONAL ARRAY, AS SHOWN IN PART I OF
O-PART SERIES OF REPORTS, IT IS SHOWN IN THIS REPORT THAT THE SAME METHOD CAN
NDED TO COVER A COMPACT ARRAY. A ONE-BIT TRANSFORM METHOD IS DESCRIBED IN
PORT WHICH CAN ACHIEVE THE SAME MONITORING PURPOSE AS THAT OF THE FOURIER
RM METHOD WITHOUT THE NECESSITY OF PERFORMING COMPLEX MULTIPLICATIONS IN THE
DR. SIMULATION OF THESE TWO APPROACHES INDICATES THAT THEY ARE ADEQUATE TO
AND LOCATE FAILURE IN BOTH THE NETWORK AND THE PHASE SHIFTERS IN A COMPACT

ARRAY.